The number of kilometer-sized near-Earth Asteroids

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In recent years, astronomers have focused their attention upon the near-Earth asteroids (NEAs), which are small (less than 10 km), generally rocky solar-system bodies with orbits approaching Earth's (perihelion < 1.3 astronomical units). Most have a ~0.5% chance of colliding with Earth in the next million years. The total number larger than 1 km has previously been estimated at 1000 to 2000, implying a ~1% chance of a catastrophic collision in the next millennium [1,2]. Because most of the threatening bodies remain undiscovered, efforts are now underway around the world to survey the population to near completeness [3]. Here, we analyze the results of the Near-Earth Asteroid Tracking (NEAT) program of the Jet Propulsion Laboratory of the California Institute of Technology and find that previous estimates for the number of NEAs with diameter d > 1 km are too large by a factor of two. At the current rate of discovery world wide, 90% will probably be discovered in the next 20 years, or in 10 years if the discovery rate is doubled.

The NEAT program is an automated search for NEAs that uses a large-format, charge-coupled device (CCD) and a 1.0-m aperture telescope at a U.S. Air Force facility on the summit of Haleakala crater on the Hawaiian island of Maui. Following by six years the first CCD detection of an NEA by the Spacewatch Telescope in 1989 [4], NEAT became the second search program to use computer software to detect NEAs in CCD images. Additional searches employing CCDs are now in operation [3]. Compared to previous photographic methods, which required a trained observer to identify asteroids by visual inspection of developed films, these automated searches are much more systematic. There is no variation in detection efficiency owing to the varying abilities of the observers. Furthermore, the automated searches provide a record of every detectable asteroid, including those in the main belt which appear ~1000 times more frequently than NEAs. The detection frequency of these additional objects, mostly left unmeasured in previous photographic searches, provides a good measure of search efficiency. The new searches thus allow a more accurate determination of the size of the NEA population.

In the period April 1996 to August 1998, NEAT searched ~35,000 square degrees of sky to limiting visual magnitude $V = 19.1 \pm 0.1$ and detected 45 NEAs. Of these, 26 have absolute magnitudes $H < 18$, which corresponds to the limit $d > 1$ km assuming an albedo of 0.10, close to the mean for larger main-belt asteroids. Table 1 shows the number detected as a function of H. Some of these were observations of previously known NEAs, but in all cases the detections were incidental - there being no knowledge that the

NEAs would appear in the survey fields. Details of the instrument, the search strategy, and an evaluation of the detection efficiency as a function of V and angular rate ω are described elsewhere [5].

To estimate the size of the total NEA population from this incomplete sampling, we use a computer program to simulate the detection by NEAT of a large, fictitious population of NEAs with random, but realistically distributed orbits. Given the known position and time of observation for each field surveyed by NEAT, and given NEAT's known detection efficiencies, the program allows us to compute the number of these fictitious NEAs that NEAT would detect as a function of H if the population were real. By adjusting the H distribution, $N(H)$, of the presampled population so that the H distribution of the simulated detections matches NEAT's real detections, the fictitious population becomes an accurate representation of the true one. We thereby constrain $N(H)$ to match the H distribution of the true population.

A similar computer simulation was used previously to determine $N(H)$ based on the observations of the Spacewatch telescope [6, 7]. Owing to uncertainties in the absolute detection efficiencies of the telescope, however, the resulting distribution was not normalized. Only the relative number of NEAs as a function of H was determined. The earlier program was also used to model the photographic detections of kilometer-sized NEAs by the Palomar Comet and Asteroid Survey (PCAS) [8]. This determined a debiased orbital distribution for the NEAs [2], used in the earlier determination of $N(H)$.

To prevent duplication of any unknown computational errors in the earlier analysis, we do not incorporate any of the software from the earlier simulation into our new program. We also use new algorithms to predict the position versus time of the NEAs and to model the search pattern. To have comparable results, however, we preserve the method used earlier to assign fictitious NEA orbits. Each assignment is random, but weighted by representation in the debiased PCAS distribution mentioned above (see Ref. 7 for a detailed discussion). To determine the dependence of V on solar phase angle, we assume a slope parameter $G = 0.15$ (defined in Ref. 9). We also assume a limiting magnitude brighter by 0.1 magnitudes than reported in Ref. 5. This correction, which accounts for the average effects of variable extinction, seeing, and telescope tracking errors, was determined from the dispersion between measured and predicted magnitudes for catalogue standards appearing in each survey field.

Figure 1 shows the resulting incremental values for $N(H)$. Each point shows the total number of NEAs for the preceding two-magnitude interval in H. The error bars take into account only the sampling uncertainty. An upper limit assuming a single detection is shown for $H = 22$ to 24 where NEAT detected no NEAs. We discuss additional systematic errors below. Figure 1 also shows the H distributions for the currently known NEAs and for the NEA population determined previously from Spacewatch observations. The Spacewatch distribution is scaled to best overlap the NEAT curve.

Comparing the NEAT and Spacewatch results, it is apparent that the measurement of $N(H)$ is repeatable. Of the six magnitude ranges from H = 14 to 26 where both curves extend, the curves deviate significantly only from H = 18 to 20. A linear fit to the NEAT curve in the range H = 16 to 22 is consistent with both data sets.

This overall correspondence can not easily be attributed to selection effects or analysis errors. Differences in the instrumentation, survey pattern, area coverage, and the dependence of search efficiency on V and ω would lead to different selection effects for the two programs. If these were improperly accounted for, or if there were computational errors in the analyses, the resulting curves would have been affected differently.

The consistency between the NEAT distribution and the known population for $H < 16$ ($d >$ ~5 km) provides additional support for our derivation. Because the known population of NEAs with $H < 16$ is nearly complete (10 of the 12 NEAs with $H < 16$ detected by NEAT were previously known, thus indicating a completeness fraction of ~80%), any significant discrepancy would have indicated an error in the analysis.

To determine the magnitude of possible systematic errors, we repeated our simulation assuming lower and higher values for the limiting magnitude (V = 18.9 an 19.1) and a higher value for the phase parameter (G = 0.23), thus covering the range of uncertainty for these parameters. In all cases, the resulting $N(H)$ curves were similar to our nominal result, with the slope from H = 14 to 24 changing by less than 2%, and the value at H = 18 changing by less than 6%.

To account for possibly uncorrected or improperly corrected observational biases in our assumed orbit distribution, we repeated the simulation once more – this time choosing random orbits from the known population of NEAs with H < 15 (41 bodies total as of July 1999, Ref. 10). Since these larger NEAs have been surveyed to near completion, their orbits are unbiased. On the other hand, their representation of all the possible NEA orbits is sparse. Hence, any deviations from our nominal derivation for $N(H)$ represent an upper limit to the possible errors. On the basis of this comparison, we determine a systematic error less than 3% in the average slope of $N(H)$, and less than 16% in the value at H = 18.

Taking into account both random and systematic errors, we thus conclude that there are 700 ± 230 NEAs with H < 18. This number is about half the value of previous estimates, but given both the old and new uncertainties we are marginally consistent with previous lower limits. This factor of two decrease does not substantially alter the significance of the NEA hazard. We have shown, however, that ongoing, automated searches provide a reliable means to characterize the size of the NEA population. We can now confidently predict the level of effort required to completely survey those NEAs capable of global devastation.

Previous survey simulations show that the number of NEAs remaining undiscovered will diminish exponentially with time if the detection rate of both known an unknown NEAs is held constant [11]. For NEAs with high and low albedos similar to the S- and C-type asteroids that dominate the main belt, limit $d > 1$ km corresponds to limits $H < 17.5$ and $H < 19.0$, respectively. Given the current yearly detection rates of 50 and 110 at these limits [10] and given our own estimates for the respective completeness levels of the known population (51 ± 17% and 26 ± 8%), it will take 7 ± 4 and 22 ± 14 years to reach 90% completion for these two types. Since the NEAs have a broad range of spectral types for which the associated albedos are largely spanned by C and S albedos [12], the time to 90% completion for all NEAs larger than 1 km is probably close to the average for these two types, or 15 ± 10 years. Doubling the current world-wide detection rate would therefore lead to near completion in the next decade.

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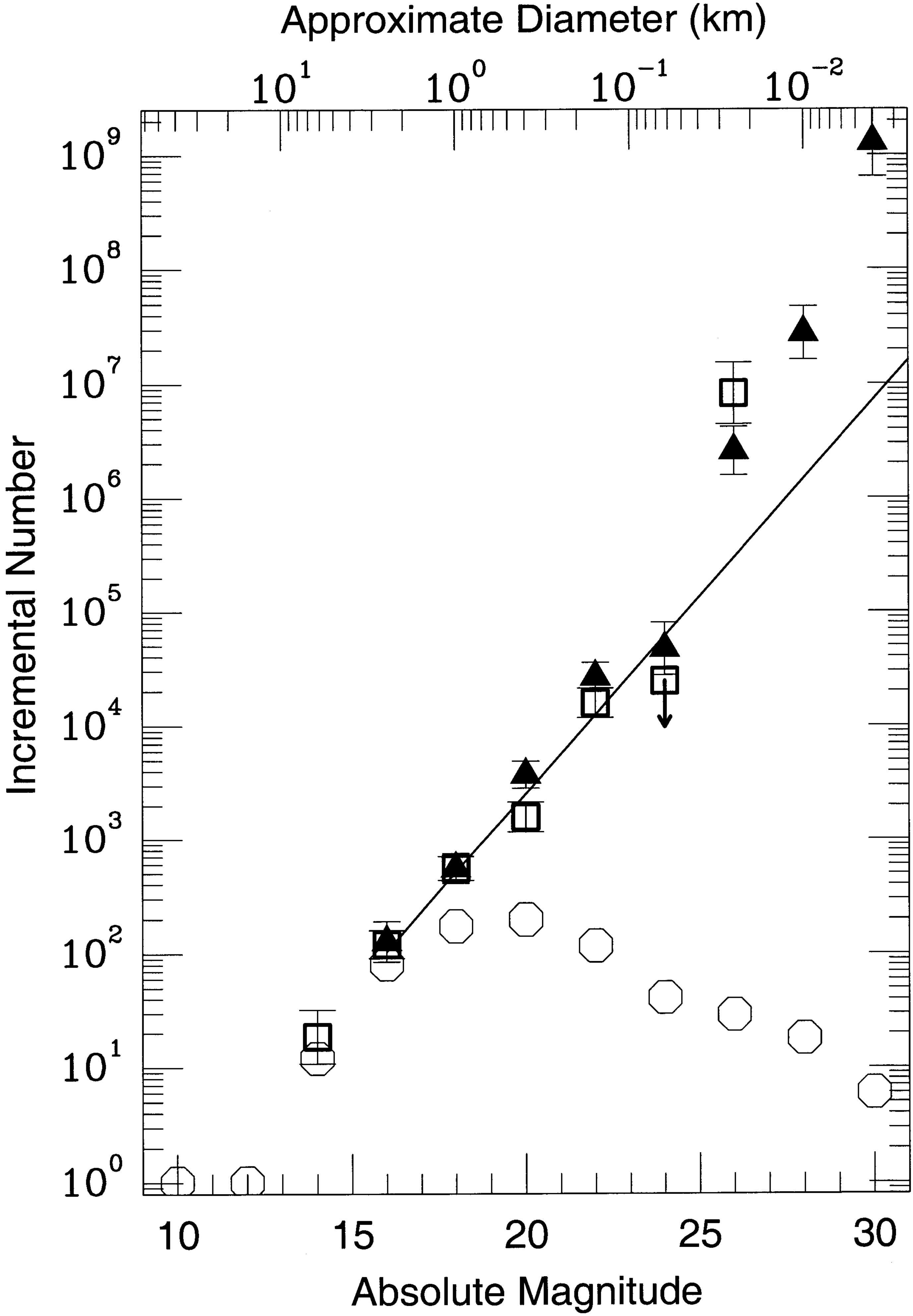
Figure Caption

FIG 1 The number of NEAs versus absolute magnitude and diameter for the total population determined by NEAT (squares) and by Spacewatch (triangle) and for the known population (octagons). Each point shows the total number of NEAs counted within the preceding two-magnitude interval. The errors bars indicate only the counting uncertainty. Additional systematic errors are discussed in the text. The solid line with slope 0.80 is a linear fit to the NEAT data in the magnitude range 16 to 22. The diameter scale is drawn assuming all NEAs have albedo 0.10, close to the mean for main-belt asteroids.

Table 1. The Number of Detected NEAs† vs absolute magnitude, H

H range	Number
12 - 14	2
14 - 16	10
16 - 18	14
18 - 20	8
20 - 22	9
22 - 24	0
24 - 26	2

†March 1996 to August 1999



Approximate Diameter (km)
10^1
10^0
10^{-1}
10^{-2}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
Incremental Number
10
15
20
25
30
Absolute Magnitude